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Assessing the environmental impact of an integrated steel mill with post-combustion CO_2 capture and storage using the LCA methodology

Dora-Andreea Chisalita [a], Letitia Petrescu [a, *], Paul Cobden [b], H.A.J (Eric) van Dijk [b], Ana-Maria Cormos [a], Calin-Cristian Cormos [a]

[a] Babes – Bolyai University, Faculty of Chemistry and Chemical Engineering, 11 Arany Janos, RO-400028, Cluj – Napoca, Romania
[b] ECN Part of TNO, Westerduinweg 3, 1755 LE, Petten, the Netherlands

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ABSTRACT

In the interest of mitigating global warming and climate change, the leading industrial sectors such as the iron and steel industry, as one of the most significant industrial contributors to anthropogenic CO_2 emissions, is challenged to find more efficient and environmentally clean solutions to reduce their CO_2 emissions while maintaining high process efficiencies and low production costs. To find new ways of reducing CO_2 or other emissions to air, water and soil, Life Cycle Assessment (LCA) methodology can be employed to trace and quantify the most significant sources of emissions, starting from the raw-materials extraction to the final product's usage/disposal. In this work, a "cradle-to-gate" LCA study was performed, according to CML 2001 impact assessment method, for an integrated steel mill with and without carbon capture and storage (CCS). Two post-combustion CO_2 capture technologies: a conventional chemical absorption technology using mono-ethanol amine (MEA) and a more innovative one based on calcium looping (CaL) are evaluated and compared against the benchmark case represented by the integrated steel mill without CCS. All results are reported on the basis of one metric ton of hot rolled coil (HRC) produced. Analysing the most significant environmental impact categories leads to the conclusion that integrating CCS into the steel production route, decreases the global warming potential in the range of 47.98–75.74%. Generally, the decrease of CO_2 emissions goes along with an increase of the other impact categories regardless of the technology used, as the adoption of CCS technologies leads to efficiency losses, which, in turn, brings additional fuel demand and related other emissions. Among the investigated capture technologies, CaL shows significantly better environmental performance than the conventional amine-based CO_2 capture technology as the decrease observed in eight of the environmental indicators, other than GWP, is between 2.90% and 48.87% compared to the case when MEA is applied.

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1. Introduction

Carbon dioxide concentrations in the atmosphere have increased rapidly over the past decades (approx. 2 ppm/year) exceeding 400 ppm in 2016 (Kahn, 2016). Globally, the industrial sector accounts for about 30% of the CO_2 emissions and one-third of the world energy demand, with the leading industries being: iron and steel, cement, chemicals and petroleum processes (IPCC et al., 2014). The main industrial CO_2 emissions are mostly energy-related, resulting either directly from burning fossil fuels either indirectly from purchasing electricity and steam. However, there are also process-related emissions which cannot be disregarded. These arise inherently from the production processes (regardless of the type of power supply) and, in most cases, they cannot be avoided (e.g. cement and lime production) (Markewitz and Bongartz, 2015).

The iron and steel industry is a significant economic and social driver, providing essential goods in various areas such as buildings and infrastructure, mechanical and electrical equipment, automotive and other transport systems, metal products and domestic appliances. Nevertheless, the iron and steel industry is the second largest industrial energy consumer and the leading industrial contributor to global anthropogenic CO_2 emissions accounting for approximately 6.7% of the total CO_2 emissions (World Steel

* Corresponding author.
E-mail address: letitiapetrescu@chem.ubbcluj.ro (L. Petrescu).

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Association, 2017).

Globally, the two most dominant steel production routes are the integrated steel mill, Blast Furnace (BF) - Basic Oxygen Furnace (BOF) route, and the mini-mill represented by the Electric Arc Furnace (EAF) route. In the integrated steel mill, steel is made by reducing iron ore in a BF followed by processing in a primary steelmaking plant. The mini-mill produces steel by melting steel scrap or other scrap substitutes such as direct reduced iron (DRI) or pig iron in an EAF, as presented in the International Energy Agency - Greenhouse Gas R&D Programme (i.e. IEAGHG) report (IEAGHG, 2013).

Literature data reports emissions between 1.6 and 2.2 t_{CO2}/t_{steel} using the BF-BOF route, while the EAF route emits between 0.6 and 0.9 t_{CO2}/t_{steel} using scrap metal and between 1.4 and 2 t_{CO2}/t_{steel} when DRI is used in the EAF route (IEAGHG, 2011). Although the EAF route has lower CO_2 emissions compared to the BF - BOF route, it should be emphasised that the two production routes are not comparable due to differences in feedstock, steel quality and products. The BF - BOF route is the predominant steelmaking route, accounting for about 70% of the world steel production (IEA, 2017). In the blast furnace, iron ore along with coke and limestone are fed at the top of the furnace and reduced counter-currently by the reducing gases passing up through the bed. The iron resulted from the BF, containing around 94% iron with more than 4% carbon content, is too brittle for most engineering applications, and is further refined into steel in the BOF steelmaking process (Lawrence Berkely National Laboratory, 2010). The reduction of iron ore requires additional heat supply, which is provided by the use of coal, coke and natural gas as reducing agents. Coal is consumed mainly in the blast furnace, where about 75% of its energy content is applied in the form of coke as a reducing agent, furnace burden support and as fuel. The rest (25%) is used in the sinter and coking plants as a heat source, and in the form of by-product gas is used as an energy source in other downstream processes (World Steel Association, 2016).

As the integrated steelmaking process depends significantly on carbon-based fuels and reductants, the iron and steel industry is challenged to find better ways of lowering CO_2 emissions without severely affecting process efficiency or substantially adding to costs (Xu et al., 2016). Two main options can be considered in order to mitigate CO_2 emissions from steel plants: increase the energy and process efficiency and/or, adopt CCS technologies.

Improving energy efficiencies and focusing on energy saving or recovering technologies (e.g. dry coke quenching and top pressure recovery turbine) can be regarded as short-term solutions for the reduction of emissions in the iron and steel industry. A cutback of 60% in the energy consumption per metric ton of steel produced has already been achieved in the last 50 years, by applying available technologies, making it more challenging for further improvements (World Steel Association, 2017).

Various potential new steelmaking technologies with a lower carbon footprint together with CO_2 utilisation have already been proposed in the literature. In Europe, Hlsarna smelter technology, developed under the Ultra-Low CO_2 Steelmaking (ULCOS) project, has been successfully tested at a pilot plant scale (Abdul Quader et al., 2016). In Japan, R&D project COURSE50 is currently preceding from a laboratory to a pilot phase (Tonomura, 2013). However, in the interest of significantly reducing CO_2 emissions from the steel industry as to meet the Two Degree Scenario (2DS) target by 2050, more advanced long-term approaches have to be adopted, such as increasing the use of renewable energy in steelmaking processes, developing and implementing CCS.

In an integrated steel mill, CO_2 comes from multiple sources, the most significant ones being an onsite power plant, the hot stoves followed by the sinter and coking plants. Three major process gases come from the BF-BOF route, namely Blast Furnace Gas (BFG), Coke Oven Gas (COG) and Basic Oxygen Furnace Gas (BOFG). Because BFG comes in larger volumes and with the highest CO_2 content while having the lowest calorific value, most of the work in developing and employing CCS in the iron and steel industry focuses on the application of CCS for BFG (Carpenter, 2012).

Most literature studies look at post-combustion capture configurations as the most suitable choice for the decarbonisation of the BFG. Various technologies are considered, with amine-based chemical absorption the most investigated option since it is the most mature CCS technology at present. Arasto et al. (2013) studied CO_2 reduction possibilities from a steel mill by applying liquid absorption using MEA as post-combustion capture technology and looking into different heat integration scenarios. An extensive study regarding the economic implications of applying CCS in an integrated steel mill was covered by IEAGHG R&D Programme (IEAGHG, 2013) examining two different capture cases: post-combustion using MEA at two different capture levels and an Oxygen Blown Blast Furnace (OBF) with top gas recycle and methyl diethanol amine (MDEA) as a solvent. Other studies look into more advanced technologies such as Pressure Swing Adsorption (PSA) (Pérez-Fortes et al., 2014) or Vacuum Pressure Swing Adsorption (VPSA) (Arasto et al., 2014), together with OBF technology as ways of reducing CO_2 emissions from an integrated steel mill. A techno-economic evaluation was performed by Cormos (2016) considering CaL as a possible option to be applied in steel mills. Combined CaL processes have also been investigated by Tian et al. (2016) who developed a new material to be used in a combined Ca-Fe chemical loop using steel slag as feedstock and by Fernández et al. (2017) who looked into the possibility of producing H_2 rich fuel gas from BFG using Ca-Cu chemical looping. As part of STEPWISE Project, Sorption Enhanced Water-Gas Shift (SEWGS) has reached TRL6 regarding design, construction, operation and modelling of a pilot installation in the Iron and Steel Industry (van Dijk et al., 2017).

This work focuses on evaluating the environmental impact of the integration of a steel mill with various CO_2 capture technologies. For comparison reasons a benchmark case represented by an integrated steel mill without CO_2 capture, was also considered. Two capture technologies were evaluated: a conventional amine-based chemical absorption process using MEA and a more innovative one based on CaL. The amine-based process is the more mature and most studied CO_2 capture technology, giving a baseline reference for comparison with other new emerging technologies. Currently, there is no literature data on LCA of steelmaking which considers the environmental impact of implementing CCS, assessing the contribution of the CO_2 capture unit and the CO_2 transport and storage step. There are various case studies regarding the environmental evaluation of steel production in different regions of the world such as Poland (Burchart-Korol, 2013) and Turkey (Olmez et al., 2016) amongst the most recent ones, focusing mainly on the environmental impact of the steel production process as a "gate-to-gate" LCA. A more extensive research was performed by the (World Steel Association, 2011) which performed a "cradle-to-gate" LCA, considering upstream processes such as raw-materials supply chain as well. In the present study, a "cradle-to-gate" LCA was performed to evaluate the environmental impact of an integrated steel mill with a capacity of 4 MMt_{HRC}/year with and without CO_2 capture.

The paper is systematised using four sections starting with an introduction into the topic and the importance of the present research. A detailed description of the cases considered and an overview of the LCA methodology used for achieving the intended goal is presented in Section 2. Finally, results and conclusions are detailed in Section 3 and 4, respectively.

2. Materials and methods

2.1. Cases presentation and modelling assumptions

As previously mentioned, an integrated steel mill coupled with two post-combustion CCS technologies was investigated leading to five case studies:

Case 1. Integrated steel mill without CCS (benchmark case);

Case 2. Integrated steel mill with CO_2 capture (from two sources) using MEA;

Case 3. Integrated steel mill with CO_2 capture (from four sources) using MEA;

Case 4. Integrated steel mill with CO_2 capture (from two sources) using CaL;

Case 5. Integrated steel mill with CO_2 capture (from four sources) using CaL.

In the benchmark steel mill, CO_2 emissions come from various sources, the five major ones being: the captive power plant, hot stoves, sinter production, coke oven batteries and the lime kiln. These emissions make up for about 90% of the total direct CO_2 emissions of the integrated steel mill (IEAGHG, 2013).

Two main carbon dioxide capture scenarios are investigated in the present work: Scenario 1 (represented by Case 2 and Case 4) in which CO_2 is captured from two major emission sources and Scenario 2 (represented by Case 3 and Case 5) where two additional CO_2 sources are added to the ones considered in Scenario 1, resulting in four CO_2 emission sources sent to the post-combustion capture units. Thus, in the MEA cases, the first scenario takes into account the CO_2 coming from the hot stoves and the steam generation plant, while in the CaL cases the CO_2 sources are represented by the hot stoves and the power plant. In the second scenario, beside the CO_2 sources presented above, other two CO_2 sources were added, more precisely the coke oven batteries and lime kiln. Regardless of the CCS technology employed, the main steel production process is not affected as the CO_2 capture section is only interfering in the power production section downstream the steel plan.

The integrated steel mill without CCS, Case 1, is based on an average Western European steel mill with a production of 4 million metric tons of HRC per year. Such a mill is described in detail in an IEAGHG report (IEAGHG, 2013). The steelmaking process includes several unit processes which are illustrated in Fig. 1.

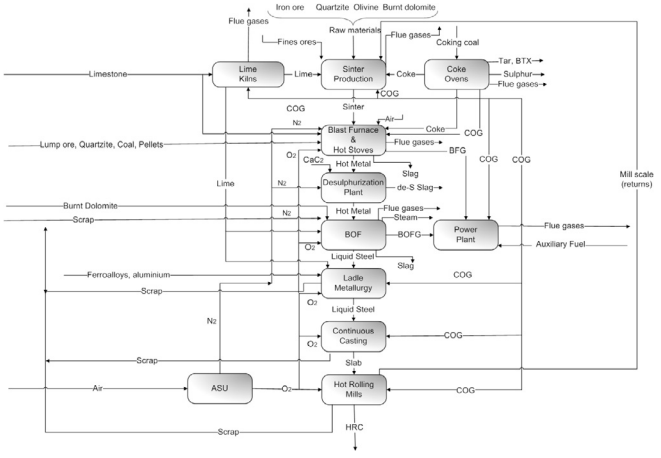

Fig. 1. Integrated steel mill.

For the benchmark case, all off-gases resulted from the coke ovens, blast furnace and basic oxygen steel furnace are used within the steel mill, and the excess is sent to the power plant as fuel. There is no import or export of utilities, coke or fuel except for natural gas import to the power plant in case the off-gas production cannot cover the fuel requirements. The coupling of a post-combustion CO_2 capture section based on chemical absorption using amines (Case 2 and Case 3) to the reference integrated steel mill leads to changes of the power plant with the addition of a steam generation plant as the electricity and steam demand will increase due to solvent regeneration. All the other processes relevant to the production of the hot-rolled coil will not be modified compared to the no-capture steel mill. In the case of the captive steel mill power plant in Case 2 and Case 3, the off-gases burned in the no-capture case for electricity generation are used to generate steam, in a steam generation plant. Additional electricity demand will be provided by a Natural Gas Combined Cycle (NGCC) power plant based on an E-Class Gas turbine with natural gas (NG) delivering approximately 192 MW_e. Hot flue gases resulting from the gas turbine will be used in a heat recovery steam generation (HRSG) unit that will supply steam at three different pressure levels from a steam turbine with a capacity of approx. 100 MW_e.

Description of the integrated steel mill with post-combustion CO_2 capture using MEA (Case 2 and Case 3) is presented below. The same IEAGHG report describing the benchmark case (IEAGHG, 2013) was used as a reference for the CO_2 capture case with MEA. The process is based on an absorption-desorption cycle in which the solvent chemically absorbs CO_2 in an absorption column, one column for each CO_2 source, followed by regeneration of the rich solvent with low-pressure steam (3–6 bar and 130–160 °C) in a desorption column (one for every two CO_2 sources) releasing the absorbed CO_2. Capture rates of 90% were assumed for each absorber, resulting in a total of 50% avoided CO_2 for the entire steel plant when capturing from the hot stoves and steam generation plant (Scenario 1) and 60% avoided CO_2 in Scenario 2, when CO_2 emissions coming from the coke oven batteries and the lime kiln are added to the ones presented in Scenario 1. Higher CO_2 avoidance ratios can be achieved if additional CO_2 sources (e.g. sinter plant) are sent to capture, but this will lead to an increase in the overall energy consumption of the reference steel mill.

The integrated steel mill using amine-based technology is presented in Fig. 2.

Energy requirements for solvent regeneration were optimised using a split flow configuration in which a part of the rich amine solution exiting the absorber is preheated using the heat of the lean amine solution coming from the stripper and then brought in a flash column where a CO_2 rich vapour is separated from the semi-lean amine. The vapour fraction goes to the stripper's condenser while the semi-lean amine solution goes to the intercooler section of the absorber. In this way, the rich amine load to be regenerated is reduced. The most relevant assumptions used in process modelling and simulation for Case 2 and Case 3 are reported in Table 1.

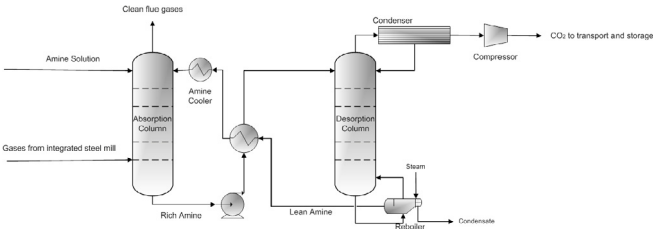

Fig. 2. *Integrated steel mill using amine-based CO_2 capture technology* (Case 2 and Case 3).

Table 1
Modelling assumptions for Cases 2 - 3.

Unit name	Assumption	Case 2	Case 3
MEA - based CO_2 capture unit	Number of absorption columns	2	4
	Number of desorption columns	1	2
	Lean-amine solution flow-rate ($t/t_{CO2\ captured}$)	21.3	48.3
	Lean-amine solution temperature (℃)	30	30
	Rich-amine solution flow-rate ($t/t_{CO2\ captured}$)	23.3	52.3
	Rich-amine solution temperature (℃)	41	41
	Split flow fraction (% rich amine solution)	40	40
	Intercooler temperature (℃)	30	30
	Stripper steam demand ($MJ/t_{CO2\ captured}$)	3.03	6.21
	Reboiler pressure (bar)	1.85	1.85
	Reboiler temperature (℃)	120	120
	MEA make-up ($kg/t_{CO2\ captured}$)	1	1
	Water make-up ($t/t_{CO2\ captured}$)	4	4.4
CO_2 compression	Delivery pressure (bar)	120	
	Compressor efficiency (%)	85	
Captured CO_2 specification	Composition (% vol.)	>95% CO_2; <2000 ppm CO; <250 ppm H_2O; <100 ppm H_2S; <4% non-condensable gases (N_2, H_2, Ar etc.)	

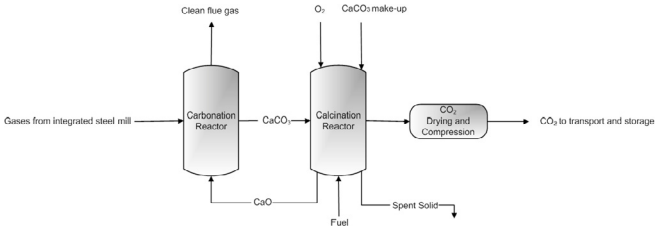

Fig. 3. Integrated steel mill using CaL technology for CO_2 capture (Case 4 and Case 5).

Details regarding the integrated steel mill with post-combustion CO_2 capture using CaL (i.e. Case 4 and Case 5) are offered in the next section. CaL is a post-combustion capture technology based on the following reversible reaction between CaO and CO_2:

$$CaO + CO_2 \rightleftarrows CaCO_3$$

Fig. 3 presents a generalised scheme of the CaL process in which the reversible carbonation/calcination reaction takes place in two inter-connected fluidised bed reactors. CO_2 from the flue gas to be treated is captured in the first reactor, called carbonator, in the form of $CaCO_3$ undergoing an exothermic reaction at temperatures around 550–600 °C. The resulted carbonate is then transferred into a second reactor, called calciner, where a pure stream of CO_2 is obtained during sorbent regeneration. The CaO formed returns to the carbonator for a new cycle. As $CaCO_3$ decomposition is strongly endothermic and takes place at high temperatures, typically 850–950 °C, additional energy is provided to the calciner by burning natural gas in an O_2 atmosphere (i.e. oxy-combustion) to prevent the captured CO_2's dilution (Perejón et al., 2016). The most significant assumptions used in process modelling and simulation for Case 4 and Case 5 are reported in Table 2.

An air separation unit (ASU) is required for O_2 generation, which produces oxygen of 95 v.% purity at an outlet pressure of 2.4 bar. A power consumption of 200 kWh/t_{O2} was assumed for the ASU. The heat generated by the exothermic reaction taking place in the carbonator is used to produce and expand steam in a steam turbine, generating electricity, some of which is used to make up for energy loses that may occur elsewhere in the process (i.e. ASU), and the rest is exported. The CaL separation process including CO_2 compression and ASU have been simulated using process simulation software ChemCAD (Chemstations, 2018).

2.2. Life Cycle Assessment (LCA)

The impact a process or product has on the environment can be assessed using the LCA methodology (Olmez et al., 2016). This valuable tool can be used to identify the most important contributors or the most important sub-processes of a more complex process and their corresponding environmental impact. Once the most significant contributors to the environment are identified, one can act on those with the aim of reducing their impact.

Standard LCA methodology is considered in the present study. The main ISO standard designed for LCA applications are ISO14040, Principles and Framework (ISO, 2006a), and ISO14044, Requirements and Guidelines (ISO, 2006b). These standards, assume four steps presented in detail in the next sections.

2.2.1. Goal and scope definition

In the first LCA phase (i.e. goal and scope definition) the main purpose of the study, the boundaries of the system and the

Table 2
Modelling assumptions for Cases 4 - 5.

Unit name	Assumption	Case 4	Case 5
Calcium looping CO_2 capture unit	Natural gas flow-rate (t/h)	38.3	63.3
	Carbonation reactor temperature (°C)	550–600	
	Calcination reactor temperature (°C)	900–1000	
	O_2 pressure to CaL unit (bar)	2.4	
CO_2 compression	Delivery pressure (bar)	120	
	Compressor efficiency (%)	85	
Captured CO_2 specification	Composition (% vol.)	>95% CO_2; <2000 ppm CO; <250 ppm H_2O; <100 ppm H_2S; <4% non-condensable gases (N_2, H_2, Ar etc.)	

functionality of the product should be specified (Pillain et al., 2017). The goal of the present LCA is to quantify and analyse the environmental impacts of steel production with/without CO_2 capture.

The scope of the LCA work includes the processes to be studied (i.e. integrated steel mill with/without CCS), the functional unit and the system boundary. The functional unit proposed is one metric ton of HRC. All the environmental key performance indicators are expressed per functional unit. The system boundaries of the present LCA are drawn around three processes: 1) upstream processes containing raw-materials extraction and transportation used in the steel production process (e.g. iron ore, metallurgical coal, limestone, quartzite, olivine); 2) main process which is represented by steel production process with all the correspondent sub-processes (e.g. coke production, sinter production, hot metal production, hot metal desulphurisation, primary and secondary steelmaking, continuous casting, reheating and rolling, lime production, air separation unit and power plant; 3) CCS processes represented by CO_2 capture units for Cases 2–5 as well as CO_2 transport and storage for the same cases. The system boundaries of the systems under study are schematically represented in Fig. 4.

Regarding the geographic and time boundaries of the investigated system, the current LCA study assumes the plant to be located in The Netherlands, coastal region, having a lifetime of 25 years. The most relevant LCA assumptions of the present study are given in Table 3.

Some limitations of the present study are explained in the next section. Downstream processing of steel into manufactured products as well as the end of life recycling of steel has not been included in the inventory. Other items excluded from the system boundaries are: *1)* construction and decommissioning of the integrated steel mill, raw-materials mines, CO_2 capture units and CO_2 transport pipelines; *2)* repair and maintenance of the machinery used in the integrated steel mill and CCS plants; *3)* construction of infrastructure (e.g. roads, railways) as well as the construction of trains and trucks for transportation; *4)* installation of railcar unloading facilities; *5)* indirect land use; *6)* human activities as well as labour costs associated with the number of employees; *7)* low - frequency, high - magnitude, non - predictable environmental events (e.g., non-routine/fugitive/accidental releases); *8)* marketing issues and *9)* operation of administration offices, etc.

The overall quality of the data is considered to be high and is representative of the systems described in terms of technological coverage.

2.2.2. Life cycle inventory (LCI)

The inputs and outputs consisting of all the raw-materials, energy, water and environmental discharges necessary to produce the functional unit are quantified in the LCI phase (Pillain et al., 2017). The material and energy balances are available from three main sources: *i)* industrial data from steel mills; *ii)* literature data from IEAGHG Report (IEAGHG, 2013) as well as from *iii)* modelling and simulation. Relevant LCI data for the processes under study are reported in Tables 4–6.

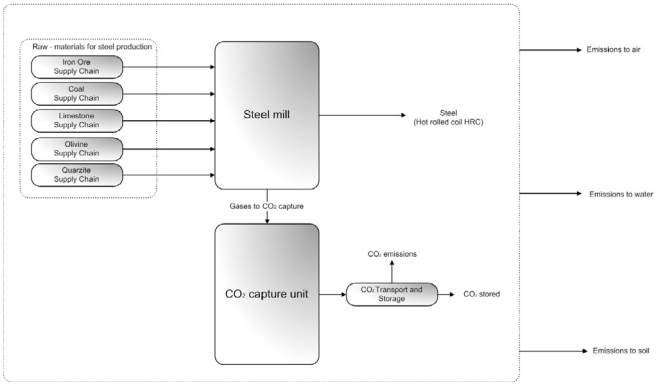

Fig. 4. System boundaries for LCA study.

2.2.3. Life cycle impact assessment

The environmental impact assessment implies the classification of the impacts into categories (Lacasa et al., 2016).

The impact categories considered in CML 2001 method are: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Depletion Potential (ODP), Aquatic Depletion Potential (ADP), Freshwater Aquatic Ecotoxicity Potential (FAETP), Human Toxicity Potential (HTP), Photochemical Oxidation Potential (PCOP), Terrestrial Ecotoxicity Potential (TEP), and Marine Ecotoxicity Potential (MAETP). These indicators are widely described in the literature (Korre et al., 2010).

3. Results and discussions

The results of the environmental evaluations for all cases are summarised in Table 7. The highest GWP corresponds, evidently, to the base case (i.e. Case 1) which represents the integrated steel mill without CO_2 capture. The introduction of the amine-based technology for CO_2 capture, using MEA as a solvent, in Scenario 1 (i.e. carbon dioxide is captured from two sources), leads to a reduction in the GWP indicator of about 47.98% compared to the base case (e.g. 1106.86 kg CO_2 equivalents/t_{HRC} vs. 2127.72 kg CO_2 equivalents/t_{HRC}) (see Case 2). If the same CO_2 capture technology is considered, but the attention is focused on Scenario 2 (i.e. carbon dioxide is captured from four sources), the GWP reduction is of about 57.80% (e.g. 897.83 kg CO_2 equivalents/t_{HRC} compared to 2127.72 kg CO_2 equivalents/t_{HRC}) (see Case 3). The same two scenarios (CO_2 from two sources and CO_2 from four sources) have been investigated considering CaL technology for CO_2 capture leading to the conclusion that the reduction of the GWP indicator is much higher when CaL technology is used in the integrated steel mill compared to the amine-based technology. When CaL is coupled with the integrated steel mill, the GWP value is reduced by 64.55% leading to a net GWP of 754.34 kg CO_2 equivalents/t_{HRC} when CO_2 is captured from two sources (i.e. Case 4), and a reduction of about 75.74% when carbon dioxide is captured from four sources (see Case 5, e.g. 516.20 kg CO_2 equivalents/t_{HRC} vs. 2127.72 kg CO_2 equivalents/t_{HRC}). Fig. 5 presents the contribution of various sub-processes of the entire supply-chain (i.e. raw-materials extraction and transportation, integrated steel mill and CO_2 transport and storage), for all cases, to the total GWP indicator.

As shown in Fig. 5, the major contributors to the GWP impact indicator, for Case 1, are the following integrated steel mill sub-processes: power plant, hot metal production, sinter production and coke production. The introduction of CCS technologies (described by Cases 2–5) reduces considerably the CO_2 emissions related to the above-mentioned steelmaking sub-processes. It is also clear that the upstream and CCS processes bring no significant contributions to the total GWP indicator. It can be observed that, when CaL is applied as post-combustion CO_2 capture, the GWP associated with the power plant shows negative values. This is a result of the subtraction of the CO_2 emissions correlated to exported electricity.

A detailed comparison of the GWP value of each sub-process corresponding to the integrated steel mill and the GWP values found in the scientific literature (IEAGHG, 2013) is displayed in Table 8, showing good agreement between the literature data and those obtained using GaBi software (PE International, 2018), the

Table 3
LCA assumptions.

Process category	Assumption
Upstream processes	*Coal extraction*
	Type - opencast
	Water consumption = 64900 kg/$t_{coal\ extracted}$
	Electricity consumption = $6.86*10^{-3}$ MJ/$t_{coal\ extracted}$
	Gaseous emissions = $8.87\ *10^{-2}$ kg CO_2/$t_{coal\ extracted}$
	Liquid emissions = 64937 kg/$t_{coal\ extracted}$
	Solid emissions = 0.675 t/$t_{coal\ extracted}$
	Coal transportation
	Transportation mode = Rail/Carrier
	Transportation rail distance = 200 km
	Transportation train capacity = 120 wagons x 75 tons
	Train energy source = electricity
	Carrier distance = 22800 km
	Carrier capacity = 170000 DWT
	Carrier fuel type = heavy fuel oil
	Iron ore extraction
	Water consumption = 100 kg/$t_{iron\ ore\ extracted}$
	Electricity consumption = 72.1 MJ/$t_{iron\ ore\ extracted}$
	Fuel consumption = 0.21 kg diesel/$t_{iron\ ore\ extracted}$
	Explosives consumption = 0.3 kg/$t_{iron\ ore\ extracted}$
	Gaseous emissions = 6.96 kg CO_2/$t_{iron\ ore\ extracted}$
	Waste water = 100 kg/$t_{iron\ ore\ extracted}$
	Iron ore transportation
	Transportation mode = Rail/Bulk Carrier
	Transportation rail distance = 900 km
	Transportation train capacity = 340 wagons x 100 tons
	Train energy source = electricity
	Carrier distance = 7600 km
	Carrier capacity = 170000–4000000 DWT
	Carrier fuel type = heavy fuel oil
	Limestone extraction[*]
	Water consumption = 6037.76 kg/$t_{limestone\ extracted}$
	Electricity consumption = 145.67 MJ/$t_{limestone\ extracted}$
	Fuel consumption = 9.95 kg natural gas/$t_{limestone\ extracted}$
	Gaseous emissions = 5.28 kg CO_2/$t_{limestone\ extracted}$
	Waste water = 6037.76 kg/$t_{limestone\ extracted}$
	Limestone transportation
	It is assumed that the limestone extraction plant is near the integrated steel mill.
Steel-making process	Steel type produced - HRC
	Annual production of 4 million metric tons of HRC
	Captive ownership of the lime plant, oxygen plant, power plant - CO_2 emissions from these facilities included in the direct emission of the integrated steel mill.
	Lump coke and coke breeze produced by the coke plant are sufficient for the steel mill demands – no import or export of coke.
	Off-gases produced by coke ovens, blast furnaces and basic oxygen steel furnaces are recovered based on industry norms and used in within the steel mill. Any excess off-gases are delivered to the captive power plant.
	Only natural gas is imported into the boundary limit to supplement any fuel requirements that are not covered by the off-gas production – no export of off-gases or other form of energy outside the boundary limit, any surplus of gases produced is assumed to be flared.
	The captive power plant produces enough electricity to fulfill the requirements of the whole steel mill specified in the boundary limits - no import or export of electricity.
	CO_2 emissions from the manufacture of purchased pellets, burnt dolomites and merchant scrap is not accounted as direct CO_2 emission.
	Granulated BF slag is not given CO_2 emission credit even if this could be considered as substitute clinker for the cement industry.
	Off-gases utilisation as fuel:
	COG supplies fuel to the coke plant, sinter plant, hot stoves, reheating furnace and lime plant; BFG supplies fuel to the hot stoves and power plant; BOFG supplies fuel to the power plant.
Downstream processes	Captured CO_2 is transported by pipeline over a distance of 800 km.
	Pipeline pressure drop = 0.06 bar/km
	CO_2 pipeline losses = 0.026%/1000 km
	Electricity consumption for CO_2 compression = 5 kWh/t_{CO2}
	CO_2 compression losses = 0.05%
	CO_2 injection pressure = 120 bar
	Electricity consumption for CO_2 injection = 7 kWh/t_{CO2}
	CO_2 injection losses = 0.1%
	Off-shore storage = North Sea
	CO_2 storage depth = 2 km

relative error being below 2.5%.

The greatest influence over the AP is brought by the extraction and transportation of iron ore, particularly by the electricity consumption for extraction (e.g. 37.20%) and transportation by rail (e.g. 59.80%). Electricity generation was assumed as a mix of various sources specific to the electricity grid of the country of exploitation (in this case Brazil): 68.60% hydro, 12.11% natural gas, 7.02% biomass, 4.66% heavy fuel oil, 2.57% nuclear and the rest is made up of lignite, wind, coal gasses, hard coal and biogas. As shown in Table 7, the lowest value for AP is obtained in Case 1 (e.g. $16 * 10^{-2}$ kg SO_2 equivalents/t_{HRC}), while the introduction of the CCS technologies, for both scenarios, leads to an increase in the AP indicator. The increase is between 14.38% and 57.50% compared to the base case. The two cases using MEA solvent (Case 2 and Case 3)

Table 4
LCI for upstream processes (Case 1 - 5).

Process	Inputs	Cases 1 - 5	Units	Outputs	Cases 1–5	Units
Coal extraction and transportation	Water	36908.07	kg/t_{HRC}	Coal	568.69	t/t_{HRC}
	Electricity for extraction	$3.90 * 10^{-3}$	MJ/t_{HRC}	Gaseous emissions		
				Carbon dioxide	0.05	kg/t_{HRC}
	Electricity for rail transport	14.64	MJ/t_{HRC}	Nitrogen dioxide	$7.36 * 10^{-7}$	kg/t_{HRC}
	Heavy fuel oil for carrier transport	6004.90	kgkm	Nitrogen monoxide	$1.05 * 10^{-7}$	kg/t_{HRC}
				Sulphur dioxide	$2.029 * 10^{-2}$	kg/t_{HRC}
				Sulphur trioxide	$1.91 * 10^{-7}$	kg/t_{HRC}
				Organic emissions to air (group VOC)	$9.60 * 10^{-3}$	kg/t_{HRC}
				Group NMVOC to air	$4.70 * 10^{-4}$	kg/t_{HRC}
				Liquid emissions	36929.09	kg/t_{HRC}
				Heavy metals to water	$4.15 * 10^{-3}$	kg/t_{HRC}
				Inorganic emissions to water	$4.32 * 10^{-2}$	kg/t_{HRC}
				Organic emissions to water	$4.72 * 10^{-4}$	kg/t_{HRC}
				Halogenated organic emissions to water	$5.68 * 10^{-12}$	kg/t_{HRC}
				Hydrocarbons to water	$1.29 * 10^{-5}$	kg/t_{HRC}
				Other emissions to water	1329.66	kg/t_{HRC}
				Water	35599.38	kg/t_{HRC}
				Solid emissions	3628.25	kg/t_{HRC}
				Heavy metals to soil	$1.49 * 10^{-9}$	kg/t_{HRC}
				Inorganic emissions to soil	$4.27 * 10^{-5}$	kg/t_{HRC}
				Organic emissions to soil	$1.02 * 10^{-9}$	kg/t_{HRC}
				Other solid emissions	3628.25	kg/t_{HRC}
				Coal transported	568.69	t/t_{HRC}
Iron ore extraction and transportation	Water	105.74	kg/t_{HRC}	Iron ore	1057.41	kg/t_{HRC}
	Electricity	76.18	MJ/t_{HRC}	Waste water	105.74	kg/t_{HRC}
	Diesel	0.22	kg/t_{HRC}	Gaseous emissions		kg/t_{HRC}
	Explosive	0.32	kg/t_{HRC}	Carbon dioxide	7.36	kg/t_{HRC}
	Electricity for rail transport	122.38	MJ/t_{HRC}	Nitrogen dioxide	$6.85 * 10^{-9}$	kg/t_{HRC}
	Heavy fuel oil for carrier transport	32228.76	kgkm	Nitrogen monoxide	$2.59 * 10^{-4}$	kg/t_{HRC}
				Sulphur dioxide	0.15	kg/t_{HRC}
				Sulphur trioxide	$1.85 * 10^{-6}$	kg/t_{HRC}
				Organic emissions to air (group VOC)	$4.55 * 10^{-2}$	kg/t_{HRC}
				Group NMVOC to air	$8.434 * 10^{-3}$	kg/t_{HRC}
				Emissions to water	124604.50	kg/t_{HRC}
				Solids emissions	$1.03 * 10^{-5}$	kg/t_{HRC}
				Iron ore transported	1057.41	kg/t_{HRC}
Limestone extraction and transportation	Water	892.63	kg/t_{HRC}	Limestone	147.84	kg/t_{HRC}
	Electricity	21.53	MJ/t_{HRC}	Waste water	892.63	kg/t_{HRC}
	Natural gas	0.03	kg/t_{HRC}	Gaseous emissions		
				Carbon dioxide	0.78	kg/t_{HRC}
				Nitrogen dioxide	$3.49 * 10^{-6}$	kg/t_{HRC}
				Nitrogen monoxide	$1.83 * 10^{-5}$	kg/t_{HRC}
				Sulphur dioxide	$9.38 * 10^{-8}$	kg/t_{HRC}
				Sulphur trioxide	$9.58 * 10^{-8}$	kg/t_{HRC}
				Organic emissions to air (group VOC)	$1.58 * 10^{-2}$	kg/t_{HRC}
				Group NMVOC to air	$4.52 * 10^{-4}$	kg/t_{HRC}
				Emissions to water	2631.45	kg/t_{HRC}
				Solids emissions	$8.17 * 10^{-5}$	kg/t_{HRC}
				Limestone transported	147.84	kg/t_{HRC}

Table 5
LCI for main CO_2 sources from steel production (Case 1).

Process	Inputs	Value	Units	Outputs	Value	Units
Hot Stoves & Recuperators	BFG	639	kg/t_{HRC}	Hot Blast to BF	1339.70	kg/t_{HRC}
	Air	1270	kg/t_{HRC}	Flue gas to stack	1096.44	kg/t_{HRC}
				27.30 (v.% CO_2)		
				0.80 (v.% O_2)		
				65.52 (v.% N_2)		
				6.38 (v.% H_2O)		
	MP Steam	7.89	kg/t_{HRC}			
	Oxygen	67.9	kg/t_{HRC}			
	COG	3.08	kg/t_{HRC}			
Captive Power Plant	Air	1280	kg/t_{HRC}	Steam (HP, MP, LP)	7.28	kg/t_{HRC}
	BFG	1250	kg/t_{HRC}	Electricity	1440	MJ/t_{HRC}
	BOFG	112	kg/t_{HRC}	Flue gas to stack	2666.2	kg/t_{HRC}
				26.43 (v.% CO_2)		
				0.71 (v.% O_2)		
				65.88 (v.% N_2)		
				6.98 (v.% H_2O)		
	NG	18.1	kg/t_{HRC}			
	Water	1740	kg/t_{HRC}			

Table 6
LCI for CCS processes: CO_2 transport & storage (Cases 2–5).

	Units	Evaluated cases			
Inputs		Case 2	Case 3	Case 4	Case 5
CO_2 captured	kg/t_{HRC}	1304.74	1532.83	1452.04	1840.87
Electricity for compressors	kWh/t_{HRC}	6.52	7.66	7.26	9.20
Electricity for injection	kWh/t_{HRC}	9.13	10.73	10.16	12.89
Outputs					
CO_2 stored	kg/t_{HRC}	1302.51	1530.21	1449.56	1837.73
CO_2 losses pipeline	kg/t_{HRC}	0.27	0.32	0.30	0.38
CO_2 losses compressors	kg/t_{HRC}	0.65	0.77	0.72	0.92
CO_2 losses injection	kg/t_{HRC}	1.30	1.53	1.45	1.84

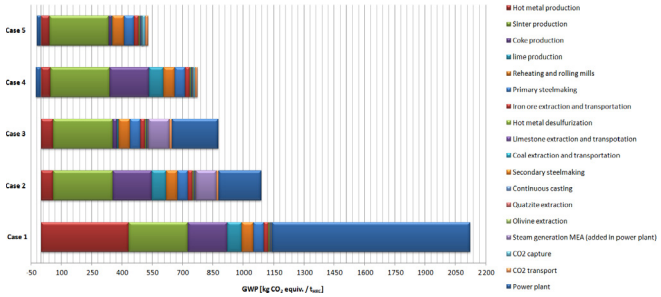

Fig. 5. Contribution of various steel mill sub-processes to the total GWP indicator.

have a higher impact than the cases based on the CaL sorbent (Case 4 and Case 5), caused by the NGCC power plant used in the MEA cases. The environmental impact of NGCC power plant, as well as the natural gas supply chain, was also considered in the LCA. The natural gas supply considers the whole supply chain of the energy carrier from exploration, production, processing and transport of the fuels to the power plants (PE International, 2018). In the case of CaL technology, natural gas required in the calciner, more precisely its supply chain (i.e. natural gas extraction and transportation), brings an additional contribution to the AP indicator compared to the benchmark case. As more natural gas is required when CO_2 is separated from four sources (see Case 5) the AP value increases as well, CaL unit taking the second position, after iron ore extraction and transportation, amongst the major contributors to AP's increase (see Fig. 6).

As in the case of AP indicator, EP indicator has also the lowest value for the benchmark case, denoted as Case 1. The highest value is obtained in Case 3 (e.g. 5.96 * 10^{-2} kg PO_4^{3-} equivalents/t_{HRC} vs. e.g. 4.08 * 10^{-2} kg PO_4^{3-} equivalents/t_{HRC}). The processes that bring additional impact to the EP indicator are the NGCC power plant and CO_2 transport and storage step in the amine-based technology (i.e. Case 2 and Case 3), respectively natural gas extraction and transportation process and CO_2 transport and storage step in the CaL technology (i.e. Case 4 and Case 5). For instance, for Case 2, from the total value of 5.80 * 10^{-2} kg PO_4^{3-} equivalents/t_{HRC}, 26.55% is due to the NGCC power plant, while 3.05% is due to the CO_2 transport and storage step. In the case of CaL technology (i.e. Case 4 and Case 5), additional fuel (i.e. natural gas) is needed in the calcination reactor to bring the reactor temperature around 1000 °C. The quantities of natural gas used in each case are 71.8 kg of natural gas/t_{HRC} for Case 4, respectively 119 kg of natural gas/t_{HRC} for Case 5. Different quantities of natural gas influence the values of EP impact indicator as follows: 1.56 * 10^{-3} kg PO_4^{3-} equivalents/t_{HRC} are the influence of natural gas extraction and transportation in Case 4, respectively 2.58 * 10^{-3} kg PO_4^{3-} equivalents/t_{HRC} is the influence of natural gas extraction and transportation in Case 5. The quantity of electricity required for CO_2 compression and injection is slightly different since different quantities of CO_2 are captured and transported in the CCS cases (Case 2 - Case 5). All these factors (higher quantity of natural gas, a higher quantity of CO_2 transported and stored) leads to a higher value for EP in Case 5 compared to Case 4.

The introduction of CCS technologies also leads to a slight increase in the ODP impact indicator between 1 and 2% compared to the reference steel mill. More than 95% of the contribution to ODP is brought by iron ore extraction and transportation, followed by CO_2 transport and storage (around 1%) and limestone extraction and transportation (0.6%). As shown in Table 7, there is no significant difference in the ODP indicator for the CCS cases (Case 2 - Case 5). CO_2 transport and storage step represents the sub-process that makes the difference regarding the ODP impact category compared to the base case, Case 1. The contribution brought by the CO_2 transport and storage step is around 1.2 * 10^{-11} kg R11 equivalents/t_{HRC} for Case 2, 1.41 * 10^{-11} kg R11 equivalents/t_{HRC} for Case 3, 1.34 * 10^{-11} kg R11 equivalents/t_{HRC} for Case 4, respectively 1.7 * 10^{-11} kg R11 equivalents/t_{HRC} for Case 5 associated to the electricity consumed for compression (42%) and injection (58%). These values are directly linked to the quantity of CO_2 captured in each case study (1304.74 kg CO_2/t_{HRC} in Case 2, 1532.82 kg CO_2/t_{HRC} in Case 3, 1452.04 kg CO_2/t_{HRC} in Case 4 and 1840.87 kg CO_2/t_{HRC} in Case 5).

The highest value for ADP_{fossil} is observed for Case 5 (e.g. 9633.70 MJ/t_{HRC}) almost doubling in value compared to the benchmark case (e.g. 9633.70 MJ/t_{HRC} vs 5332.39 MJ/t_{HRC}). When CO_2 is captured using MEA, Case 2 and Case 3, additional contribution to the ADP_{fossil} impact indicator, compared to the benchmark case (Case 1), is brought by the NGCC power plant, more specifically by the electricity generated from natural gas (e.g. 3838.21 MJ/t_{HRC} for Case 2 respectively 4166.72 MJ/t_{HRC} for Case 3). For the CaL cases (i.e. Case 4 and Case 5) a significant contribution is brought by the natural gas used in the calciner (e.g. 2969.84 MJ/t_{HRC} for Case 4, respectively 4909.94 MJ/t_{HRC} for Case 5). Electricity for CO_2 compression and injection brings a smaller contribution in all evaluated scenarios (e.g. 99.24 MJ/t_{HRC} for Case 2, 116.59 MJ/t_{HRC} for Case 3, 110.44 MJ/t_{HRC} for Case 4 and 140.01 MJ/t_{HRC} for Case 5).

The major contributors to the FAETP and HTP indicators are the

Table 7
LCA results (Cases 1–5) according to CML 2001.

KPI	Units	Case 1	Case 2	Case 3	Case 4	Case 5
GWP	kg CO_2 equivalents/t_{HRC}	2127.72	1106.86	897.83	754.34	516.20
AP * 10^2	kg SO_2 equivalents/t_{HRC}	16.00	24.40	25.20	18.30	19.60
EP * 10^2	kg PO_4^{3-} equivalents/t_{HRC}	4.08	5.80	5.96	4.40	4.55
ODP *10^{10}	kg R11 equivalents/t_{HRC}	12.88	13.03	13.05	13.03	13.08
ADP fossil	MJ/t_{HRC}	5332.39	9269.82	9615.7	7664.03	9633.70
FAETP * 10^2	kg 1,4 DCB equivalents/t_{HRC}	28.80	34.30	34.90	30.60	31.60
HTP	kg 1,4 DCB equivalents/t_{HRC}	4.43	7.71	8.01	4.77	4.90
PCOP * 10^2	kg ethylene equivalents/t_{HRC}	1.00	2.66	2.80	1.36	1.61
TEP * 10^1	kg 1,4 DCB equivalents/t_{HRC}	1.27	1.38	1.40	1.34	1.37
MAETP	kg 1,4 DCB equivalents/t_{HRC}	4744.96	5559.04	5690.17	5577.64	5840.75

Table 8
GWP results comparison.

Source of CO_2 emissions	Reported emissions (kg/t_{HRC})			LCA results (kg/t_{HRC})		
	No Capture	Capture with MEA		No Capture	Capture with MEA	
		Scenario 1 2 sources	Scenario 2 4 sources		Scenario 1 2 sources	Scenario 2 4 sources
Coke oven (flue gases & flare)	194.67	194.67	22.44	194.25	194.24	22.01
Sinter Plant (flue gases)	289.46	289.44	289.44	292.52	292.52	292.52
Hot stoves (flue gases)	415.19	41.51	41.51	414.64	41.46	42.46
HM desulphurisation & Ancillaries	7.76	7.76	7.76	5.36	5.36	5.36
Blast furnace (flare)	19.73	19.73	19.73	19.72	19.72	19.72
Blast Oxygen Furnace (BOF)	51.02	51.02	51.02	52.35	52.35	52.35
Continous casting (difuse emissions)	0.80	0.80	0.80	0.80	0.80	0.80
Reheating furnaces (flue gases)	57.71	57.71	57.71	57.69	57.69	57.69
Hot rolling mills (diffuse emissions)	0.04	0.04	0.04	0.04	0.04	0.04
Lime plant (flue gases)	71.62	71.62	7.16	71.53	71.53	7.12
Power plant (flue gases)	982.13	210.80	227.31	981.06	225.95	245.29
Steam generation plant (flue gases)	–	96.61	102.50	–	96.91	102.71
TOTAL EMISSIONS	**2090.13**	**1041.71**	**827.42**	**2089.96**	**1058.58**	**846.71**

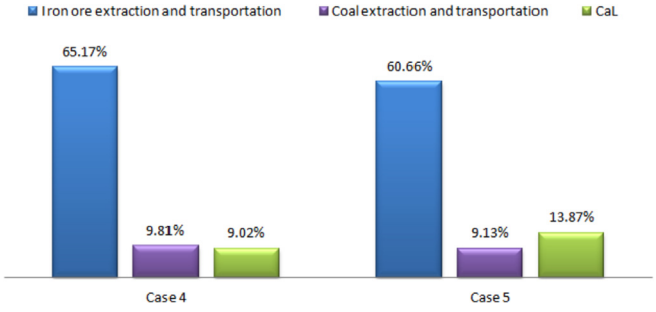

Fig. 6. Main contributors to AP indicator (Case 4 and Case 5).

upstream processes, mainly iron ore extraction and transportation (84.62%), coal extraction and transportation (9.04%) and limestone extraction and transportation (3.45%). Only a small share of 1.79% is accountable to the steelmaking process, the main contributors being the primary steelmaking and the power plant with 41.65% and respectively 29.70% out of the total share of the steelmaking process. The introduction of CCS technologies leads to higher FAETP and HTP impact indicators, especially for the MEA cases. In all cases, the primary contributors to these indicators remain the iron ore and coal extraction and transportation. The major contributor to the HTP increase, in Case 2 and Case 3, is the NGCC power plant which has a share of 39.42% and 41.18% respectively from the total impact indicator's value. The CO_2 transport and storage bring a smaller share to the HTP with a contribution of 3.1% for Case 2 and 3.47% for Case 3. For the CaL cases (i.e. Case 4 and Case 5) the increase of these indicators is brought by the CO_2 transportation and storage process and natural gas supply chain. For the HTP impact indicator, out of the total 4.77 kg 1,4 DCB equivalents/t_{HRC} for Case 4, $2.63 * 10^{-1}$ kg 1,4 DCB equivalents/t_{HRC} are brought by the CO_2 transport and storage and $9.4 * 10^{-2}$ kg 1,4 DCB equivalents/t_{HRC} by the natural gas extraction and transportation. The same processes bring in Case 5 an additional $3.34 * 10^{-1}$ kg 1,4 DCB equivalents/t_{HRC} from the CO_2 transport and storage and $1.55 * 10^{-1}$ kg 1,4 DCB equivalents/t_{HRC} from the natural gas supply chain, compared to the base case (Case 1).

Photochemical Oxidation Potential (PCOP) has the lowest value obtained in the benchmark case (e.g. 10^{-2} kg ethylene equivalents/t_{HRC}). The major contributors to this impact category and their correspondent percentages are: iron extraction and transportation 70.30%, coal extraction and transportation 9.36%, power plant 8.79%, limestone extraction and transportation 5.55%, primary steelmaking process brings a contribution of 2.41% from the total PCOP indicator. The PCOP value for Case 2 is $2.66 * 10^{-2}$ kg ethylene equivalents/t_{HRC}. The major contributor to Case 2 is represented by the NGCC power plant with a contribution of 59% of the total value. An additional contribution to this impact category, compared to the base case, is brought by the CO_2 transport and storage process, more exactly by the electricity required for CO_2 compression and injection with a share of 3%. For Case 3, PCOP is $2.80 * 10^{-2}$ kg ethylene equivalents/t_{HRC}. More than half of this quantity is due to the NGCC power plant, while a relatively small contribution of 3.34% is due to the CO_2 transport and storage section. For CaL technologies additional contributions are caused by the natural gas supply chain (e.g. 25.66% Case 4 and 35.78% Case 5) and by the CO_2 transport and storage (e.g. 6.51% Case 4 and 6.96% Case 5). As previously mentioned, natural gas is used in the calcination reactor.

Terrestrial Ecotoxicity Potential (TEP) is another indicator where the CCS cases have higher values than the benchmark case. The following processes represent the significant contributors to this impact indicator in the base case, Case 1: iron ore extraction and transportation (e.g. 75.83%), primary steelmaking (e.g. 9.76%), coal extraction and transportation (e.g. 4.77%), secondary steelmaking (e.g. 2.65%), limestone extraction and transportation (e.g. 2.47%) and a smaller contribution from the rest of the processes. According to Table 7, there are no significant differences in the TEP values for CCS cases under study, Cases 2–5. Apart from the above mentioned processes, which influence all the case studies, other specific processes, belonging to the CCS cases, that bring additional contribution to the TEP, are: CO_2 transport and storage (for Cases 2–5), NGCC power plant (e.g. 4.11% for Case 2 and 4.39% for Case 3) and natural gas extraction and transportation (e.g. 1.02% for Case 4 and 1.64% for Case 5).

For Marine Aquatic Ecotoxicity Potential (MAETP) impact indicator, the lowest value is obtained in the benchmark case (e.g. 4744.96 kg 1,4 DCB equivalents/t_{HRC}). The major contributors to this impact category are: iron extraction and transportation 83.3%, limestone extraction and transportation 5.4%, coal extraction and transportation 5.2%, primary steelmaking process brings a contribution of 2.3%, and the other processes represent 3.75%. For Case 2, additional contribution to this impact category, compared to the base case, is brought by the CO_2 transport and storage process (e.g. 688.66 kg 1,4 DCB equivalents/t_{HRC}) and by the NGCC (e.g. 125.42 kg 1,4 DCB equivalents/t_{HRC}). MAETP indicator in Case 3 is 5690.17 kg 1,4 DCB equivalents/t_{HRC}, out of which a quantity of 809.05 kg 1,4 DCB equivalents/t_{HRC} corresponds to the CO_2 transport and storage and 136.15 kg 1,4 DCB equivalents/t_{HRC} corresponds to the NGCC, more specifically by the electricity generated using natural gas as fuel. For the CaL cases (Case 4 and Case 5) the main process that

contributes to the increase of the MAETP indicator is the CO_2 transport and storage section. For instance, in Case 4, the contribution of CO_2 transport and storage represents 766.41 kg 1,4 DCB equivalents/t_{HRC}, while for Case 5 the same process represents a quantity of 971.64 kg 1,4 DCB equivalents/t_{HRC}. A smaller contribution is brought by the natural gas extraction and transportation used in the calciner, accounting for 88.6 kg 1,4 DCB equivalents/t_{HRC} in Case 4, respectively 146.48 kg 1,4 DCB equivalents/t_{HRC} for Case 5.

Comparing the two CO_2 capture technologies investigated in the present research paper for each scenario (i.e. Scenario 1: Case 2 vs. Case 4 and Scenario 2: Case 3 vs. Case 5) it can be noticed that, from a total number of ten environmental impact categories, eight of them, more precisely GWP, AP, EP, ADP_{fossil}, FAETP, HTP, PCOP, TEP, have lower values when CaL is used for CO_2 capture. ODP indicator has the same value for Scenario 1, while MAETP impact indicator has a higher value in Case 4 compared to Case 2. The situation is quite similar for Scenario 2 leading to the conclusion that CaL represents a more environmentally friendly design.

4. Conclusions

The environmental evaluation of an integrated steel mill coupled with post-combustion CCS technologies was discussed in this paper. Two CO_2 capture technologies have been investigated. The first one is a conventional technology based on amine gas-liquid absorption, using MEA as solvent, while the second technology is a more innovative one based on calcium looping CO_2 capture. For comparison reasons, an integrated steel mill without CCS was also considered. Two scenarios have been considered in the present research study. The first scenario, Scenario 1, takes into account two main CO_2 sources, more precisely the CO_2 coming from the hot stoves and the steam generation plant/power plant. In the second scenario, Scenario 2, two additional CO_2 sources, coke oven batteries and lime kiln, are considered. CO_2 capture rates higher than 90% for both CCS technologies were reached.

The environmental impact assessment was performed using the LCA methodology, implemented in GaBi software. CML 2001 was considered as impact assessment method. The environmental assessment is based on three data sources: industrial data, literature data as well as process modelling and simulation data. A "cradle-to-gate" approach was used, and several upstream and downstream sub-processes were considered in the LCA. Ten environmental impact categories were defined, calculated and compared among various evaluated integrated steel mill with and without CO_2 capture. Discussions about all indicators are reported in the paper. As the results show, the introduction of post-combustion CCS technologies has significant environmental benefits in term of reducing GHG emissions. For instance, when MEA solvent is used for CO_2 capture, Scenario 1, the reduction in the GWP indicator, compared to the base case, is about 47.98%. If the same CO_2 capture technology is considered, but the attention is focused on Scenario 2 (i.e. carbon dioxide is captured from four sources) the GWP reduction is of about 57.80%. When CaL is coupled with the integrated steel mill, the GWP value is reduced by 64.55% in Scenario 1, and a reduction of about 75.74% is obtained in Scenario 2 when carbon dioxide is captured from four sources. The error obtained when GWP values were compared against literature data was less than 2.5% leading to the conclusion that the LCA method used is reliable.

The introduction of CCS technologies leads to a significant decrease in the GWP indicator, while all other environmental indicators have a more or less significant increase compared to the benchmark case. The increase is mainly due to the addition of a NGCC power plant for amine-based cases, extraction and transportation of the natural gas used in the calcination reactor, as well as the supply chain for the electricity used by CCS processes (i.e. CO_2 transport and storage step), steps that are not present in the benchmark case.

Comparing the innovative post-combustion technology based on calcium looping against the conventional amine-based technology, from a total number of ten environmental impact categories, eight of them, have lower values when CaL is used for CO_2 capture. The decrease of the eight environmental categories is in the range 2.90%–48.87% for Scenario 1, respectively in the range 0.72%–39.47% for Scenario 2. These decreases can lead to the conclusion that CaL represents a more environmentally friendly design than the amine-based CO_2 capture technology.

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Nomenclature

ADP	Abiotic Depletion Potential
AP	Acidification Potential
ASU	Air separation unit
BF	Blast Furnace
BFG	Blast Furnace Gas
BOF	Blast Oxygen Furnace
BOFG	Basic Oxygen Furnace Gas
CML	Centre of Environmental Science, University of Leiden, The Netherlands
CaL	Calcium Looping
CCS	Carbon Capture and Storage
COG	Coke Oven Gas
DRI	Direct Reduced Iron
DWT	Deadweight tonnage
EAF	Electric Arc Furnace
EP	Eutrophication Potential
FAETP	Freshwater Aquatic Ecotoxicity Potential
GWP	Global Warming Potential
HP	High Pressure
HM	Hot Metal
HRC	Hot Rolled Coil
HRSG	Heat Recovery Steam Generator
HTP	Human Toxicity Potential
IEAGHG	International Energy Agency Greenhouse Gas R&D Programme
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LP	Low Pressure
MAETP	Marine Aquatic Ecotoxicity Potential
MEA	Mono-ethanol amine
MDEA	Methyl diethanolamine
MP	Medium Pressure
NG	Natural Gas
NGCC	Natural Gas Combined Cycle
NMVOC	Non Methane Volatile Organic Compound
ODP	Ozone Layer Depletion Potential
OBF	Oxygen Blown Blast Furnace
PCOP	Photochemical Ozone Creation Potential
PSA	Pressure Swing Adsorption
R&D	Research and Development
SEWGS	Sorption Enhanced Water-Gas Shift
TEP	Terrestrial Ecotoxicity Potential

VOC	Volatile Organic Compound
VSPA	Vacuum Pressure Swing Adsorption
WGS	Water Gas Shift
WSA	World Steel Association
2DS	2 Degree Scenario

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